Strong and Electromagnetic Forces in Heavy Ion Collisions*

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The interplay between the strong and electromagnetic force in high energy nucleus-nucleus collisions was studied experimentally and theoretically in our earlier works. This effect appeared to result in very large distortions in spectra of charged pions produced in the collision. It was also found to bring new, independent information on the space-time evolution of the non-perturbative process of particle production. In this paper, we present our new results on the influence of the spectator-induced electromagnetic force on spectra of charged particles produced in two different Pb-induced reactions. For the first time, we also address the topic of p+A collisions in view of obtaining information about their centrality and nuclear break-up, both subjects being of importance in the context of the new p+A data collected at the LHC.

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1. Introduction

This paper addresses a specific class of nucleus-nucleus collisions, where a large "spectator system" survives. Such specific reactions give the opportunity to investigate the interplay between phenomena occurring in the participant and spectator zones. In particular, this is the case for our study which concerns the interplay between the strong and electromagnetic forces in such reactions. This can be used as a new source of information on the collision dynamics.

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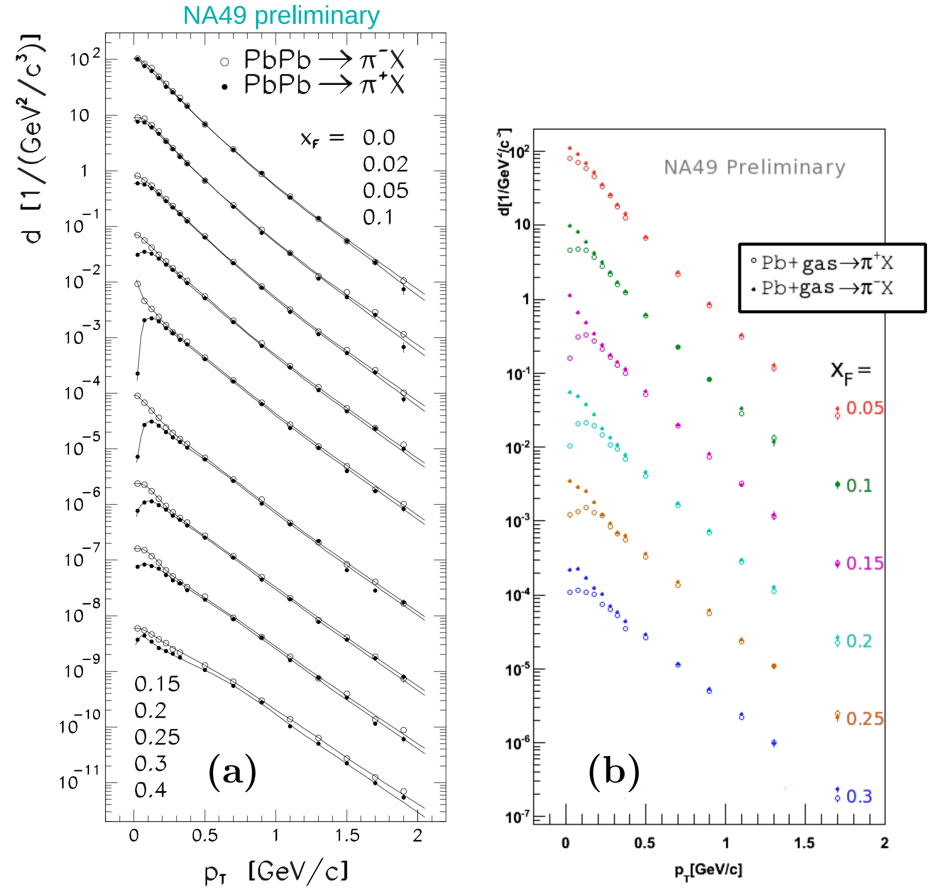

Fig. 1. Invariant density $d = E\frac{d^3n}{dp^3}$ of positive and negative pions produced in (a) peripheral Pb+Pb and (b) Pb+gas collisions, drawn as a function of pion transverse momentum at fixed values of x_F (listed from the top to the bottom distribution). Note: for clarity, the subsequent distributions are multiplied by (a) 1, 0.1, 0.01, 10^{-3}, 10^{-4}, $2 \cdot 10^{-6}$, 10^{-7}, 10^{-8}, 10^{-9}, and by (b) 1, 0.1, 0.01, 10^{-3}, 10^{-4}, 10^{-5}. The data come from (a) [1, 2] and (b) [3].

2. The data

All the studies summarized in this paper were inspired by experimental observations made in the SPS energy regime (beam energy of 158 GeV/nucleon, $\sqrt{s_{NN}}$ = 17.3 GeV). These were coming from two data sets, both collected by the NA49 experiment [4]. The first was a sample of peripheral Pb+Pb reactions, defined by a cut of 150-300 charged particles measured by

the NA49 detector [1]. This corresponded to an average number of 54±11 participating nucleons and a mean impact parameter of 10.9±0.5 fm [2]. The second data set was a sample of "Pb+gas" events, i.e. collisions of the Pb beam projectiles with nuclei of gas surrounding the NA49 target [3]. These collisions (mostly Pb+N, Pb+O) were experimentally isolated by means of proper interaction vertex cuts, together with the same cut on measured multiplicity as given above [5]. It is therefore expected that the corresponding mean number of participating nucleons was roughly comparable to that in peripheral Pb+Pb reactions. The double differential spectra of positively and negatively charged pions produced in both reaction samples are shown in Fig. 1. They are drawn as a function of transverse momentum p_T at fixed values of the Feynman variable[1] $x_F = \frac{2p_L}{\sqrt{s_{NN}}}$.

3. The ratios $\frac{\pi^+}{\pi^-}$ in Pb+Pb and Pb+gas events

Figs 2(a) and 2(b) show the ratios of positively over negatively charged pions produced in peripheral Pb+Pb and Pb+gas collisions, respectively. The similarity of the evolution of the ratios with x_F and p_T in the two collision types is evident. In both cases, the $\frac{\pi^+}{\pi^-}$ ratio displays a steep, rapidly varying structure, with a deep minimum at low transverse momenta where it comes below 0.2. Account taken of the comparable number of protons and neutrons participating in both reactions (40% over 60% for the Pb nucleus), such a low value of this ratio breaks isospin symmetry. This demonstrates that the strong interaction cannot be the sole responsible for this effect. The position of the minimum ($x_F \approx 0.15 = \frac{m_\pi}{m_N}$) corresponds to pions moving longitudinally with spectator velocity. Indeed, the effect is caused by the *electromagnetic interaction between charged pions and the spectator system*. The repulsion of positive pions results in the depopulation of the region $x_F \approx 0.15$, low p_T, while the attraction of negative pions causes their accumulation in the same region of phase space (see also Fig. 1).

In order to quantify this hypothesis, we constructed an intentionally simplified model of the peripheral Pb+Pb collision, taking the spectator-induced electromagnetic interaction into account [1, 6]. This is illustrated in Fig. 2(d). The two spectator systems are modeled as two Lorentz-contracted, uniformly charged spheres. Charged pions are emitted from a single point in space (the interaction point). The time of pion emission t_E is a free parameter of the model, defining the initial conditions for the electromagnetic interaction. Initial spectra of pions are assumed to be equal to these in the mixture of nucleon-nucleon (p+p, n+p, p+n, n+n) collisions. They are constructed on the basis of NA49 p+p data [8]. Proper account

[1] All the kinematical variables will always be defined in the collision c.m.s.

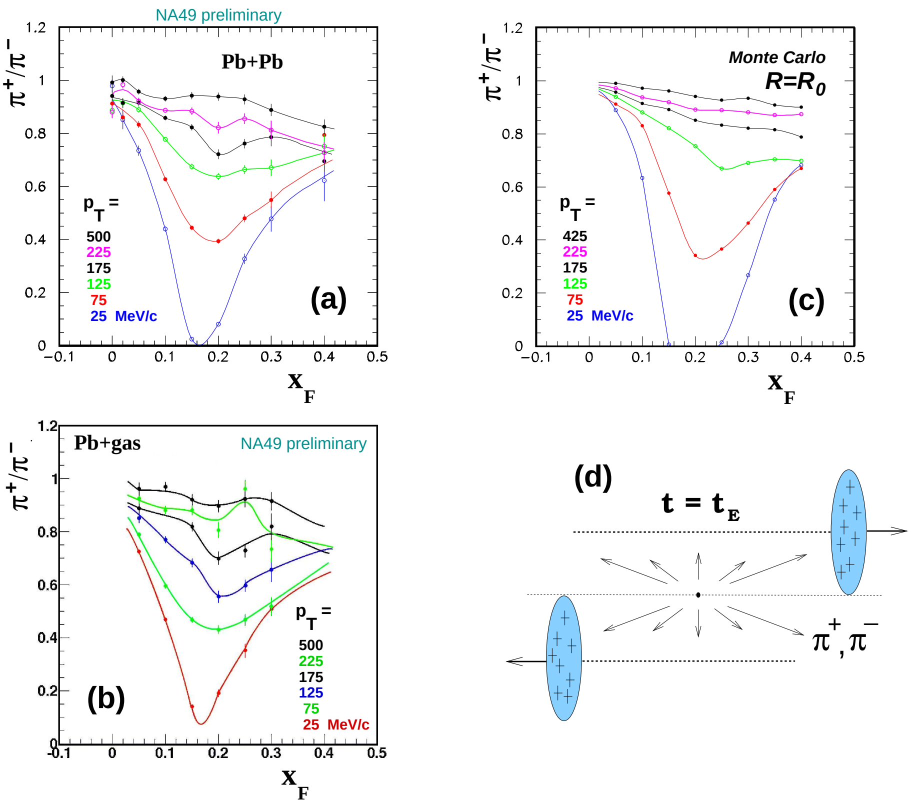

Fig. 2. (a) $\frac{\pi^+}{\pi^-}$ ratio in peripheral Pb+Pb reactions, (b) the same ratio in Pb+gas collisions, (c) model simulation as described in the text, (d) schematic illustration of the model. The data in panel (b) come from [3]. Other panels come from [7].

is taken of isospin symmetry and of the proton/neutron ratio in the Pb nucleus (40%/60%); details of this procedure can be found in [9]. Charged pions are then numerically propagated in the electromagnetic field of the spectators. Relativistic effects such as retardation are taken into account.

As it can be seen in Fig. 2(c), the model gives a fair description of the main features of the peripheral Pb+Pb data, Fig. 2(a). It is to be noted that the simulation presented here assumes a mixed set of initial conditions with 50% of events generated with $t_E = 0.5$ fm/c and the remaining 50% generated with $t_E = 1$ fm/c. This means that the pion formation site is placed "behind" the nearest spectator system as discussed in [2]. The only region where a more significant disagreement between data and model can be seen is $x_F \approx 0.2$, low p_T. This has been identified as resulting from the *fragmentation (break-up) of the spectator system*, and yielding in fact independent information on the space-time evolution of this process [10].

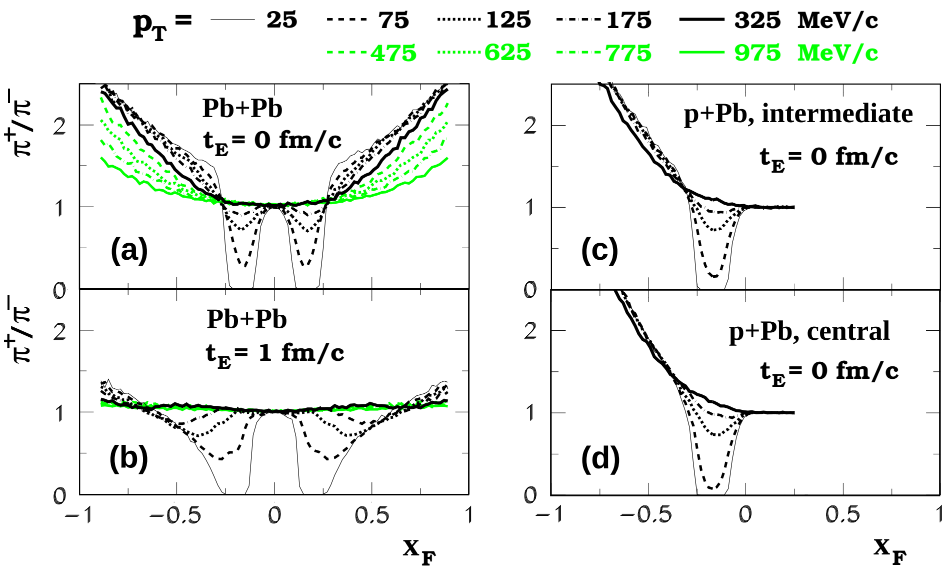

Fig. 3. $\frac{\pi^+}{\pi^-}$ ratio in peripheral Pb+Pb reactions (a,b), intermediate p+Pb collisions (c) and central p+Pb collisions (d). Note that the simulation of Pb+Pb reactions extends further in p_T relative to our earlier work [6].

4. $\frac{\pi^+}{\pi^-}$ ratios over full phase space

Account taken of the success of our model in describing the basic features of the experimental data, we decide that it may be applied with some confidence to investigate the electromagnetic distortion of $\frac{\pi^+}{\pi^-}$ ratios in the full range of x_F. The results of our simulations[2] are shown in Fig. 3. As apparent in Fig. 3(a), the two-dimensional electromagnetic distortion seen in the data in Section 3 is in fact part of a larger structure, consisting of two symmetric "holes" in the $\frac{\pi^+}{\pi^-}$ ratio, accompanied by a possible rise at higher absolute x_F. It is interesting to note that the region of sensitivity to the electromagnetic effect extends, at high x_F, to relatively large transverse momenta, up to and above $p_T = 1$ GeV/c.

Comparison with Fig. 3(b) demonstrates the sensitivity of the spectator-induced electromagnetic distortion to the pion emission time t_E. This shows the important ability of the electromagnetic effect to constrain possible scenarios and to provide new information on the space-time evolution of the process of pion production, see also [1, 6, 7, 10].

[2] Note: for simplicity, this version of our simulation neglects the differences between initial π^+ and π^- spectra, resulting from the excess of neutrons in the Pb nucleus (these differences were taken into account in the previous Section). This implies that any deviation of the $\frac{\pi^+}{\pi^-}$ ratio from unity will solely be due to electromagnetic effects.

Finally, the electromagnetic effect in intermediate and central p+Pb reactions is shown in Figs 3(c) and 3(d). With the trivial exception of the "one-hole" structure imposed by the presence of a single spectator nucleus, the similarity to peripheral Pb+Pb collisions, Fig. 3(a), is evident. Little dependence on pure geometry (centrality) of the p+Pb collision is apparent in the Figure. This gives a relatively well defined situation for using the electromagnetic interaction as source of information on pion production and on its interplay with nuclear fragmentation, also in p+A collisions.

5. Conclusions & outlook

The spectator-induced electromagnetic effect discussed in this paper influences a number of observables in various types of nuclear collisions (p+A, Pb+gas, Pb+Pb, etc). The well-defined nature of the electromagnetic interaction makes it a convenient tool to provide independent information on the space-time evolution of the reaction. However, only a few phenomena have been addressed here. Other examples can be quoted. Among these, the electromagnetic effect induced on kaon spectra [7], on azimuthal anisotropies (directed flow), its possible presence in "ultra-peripheral" Pb+Pb collisions [11], and many others are presently under active investigation.

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